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A Review of Fairness Conceptualizations in Electrical Distribution Grid Congestion Management

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***Abstract*—Fairness has recently gained significant attention in the scientific literature on algorithmic control systems for congestion management. However, many diverse conceptualizations of fairness have been presented. This paper aims to categorize these varying conceptualizations by reviewing existing literature on congestion management. It examines how researchers approach decisions concerning the scoping of fairness problems, the selection of fairness principles, and the choice of evaluation metrics. Findings highlight a need for more justification of fairness conceptualizations in literature as well as a need for standardized evaluation metrics and more empirical grounding and validation. The insights provided can help researchers and practitioners consider fairness comprehensively in the design of algorithmic control systems for congestion management.**

***Index Terms*—congestion management, fairness, electrical distribution grids, algorithmic control systems**

I. Introduction

The rapid expansion of distributed renewable energy generation and increased electrification is challenging the operation of electrical distribution grids. The corresponding growing power consumption and supply are increasingly leading to grid congestion, characterized by overloading and voltage deviations [1]. Traditionally, distribution system operators have addressed grid congestion by reinforcing infrastructure, but constraints such as technician shortages, spatial procedures, land limitations, and financing options hinder their efforts [2]. An alternative approach focuses on leveraging grid flexibility to shift loads away from congested points, requiring active involvement from prosumers using algorithmic control systems, also known as congestion management [3].

Next to technical challenges, congestion management introduces new questions for distribution system operators regarding fairness [4]. For instance, it is known that curtailment algorithms for maintaining voltage levels might disproportionately favor parties near a substation over others [5]. Researchers in power systems have therefore emphasized the importance of considering fairness in congestion management decisions (e.g. [6, 7]). However, many different conceptualizations of fairness have been presented in the literature [3].

Similar developments have been observed in computer science literature, where Gajane and Pechenizkiy [8] emphasized that there is no agreement among computer scientists about which fairness conceptualization is the most appropriate. Moreover, Castelnovo et al. [9] showed that satisfying different fairness conceptualizations at the same time is impossible. So, broadly supported norms and standards are required to ensure that the fairness conceptualizations considered in algorithmic control systems for congestion management are in line with societal needs and expectations. However, these norms and standards are still missing.

We therefore need a more comprehensive understanding of how fairness can or ought to be conceptualized in the context of congestion management. Despite the increasing number of papers addressing fairness in algorithmic control systems for congestion management, a comprehensive review of the various fairness conceptualizations remains lacking. This literature review aims to fill this gap by categorizing fairness conceptualizations in algorithmic control systems for congestion management. Our overview therefore aims to inform a more rigorous grounding of fairness conceptualizations for future researchers and to guide efforts for the development of shared norms and standards for fairness in this context.

Our main research question is therefore: *How do different scientific studies conceptualize fairness in the context of congestion management?* This paper is organized as follows: Section II describes the methodology of this literature review. Subsequently, we analyze and categorize three key aspects across all fairness conceptualizations: scoping decisions made (Section III), fairness principles considered (Section IV), and evaluation metrics used (Section V). Finally, Sections VI and VII provide the discussion and conclusion respectively.

II. Methodology

The literature search was conducted using IEEE Xplore and Scopus databases. The search keywords are shown in Table I, and the search query was: *'(A) AND (B) AND (C) AND (D)'*. Conducted on May 1st, 2024, the search spanned from 2009 to 2024. Only articles published in English were considered.

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TABLE I
LITERATURE SEARCH KEYWORDS

Group	Keywords
(A)	‘fairness’ OR ‘non-discrimination’ OR ‘justice’
(B)	‘congestion’ OR ‘demand response’ OR ‘curtailment’ OR ‘voltage control’
(C)	‘distribution’
(D)	‘power’ OR ‘electrical’ OR ‘grid’

TABLE II
SCOPING DECISIONS IN SELECTED ARTICLES

Scoping decisions	Options presented in selected articles
Motivation	Public acceptance (e.g. [10, 11]) Unfair voltage control (e.g. [12, 13]) General ‘unfairness issues’ (e.g. [14])
Congestion type	Over/under-voltage (e.g. [15, 16, 17]) Cable overloading (e.g. [1, 7, 18]) Transformer overloading (e.g. [19, 20, 21])
Application area	Photovoltaic systems (e.g. [3, 5, 22, 23]) Electric vehicles (e.g. [24, 25, 26]) Distributed energy resources (e.g. [27, 28]) Demand response (e.g. [11, 29, 30, 10])
Distributed burden or benefit	Power reduction amount (e.g. [31, 32, 33, 6]) Power reduction time (e.g. [22]) Power provision amount (e.g. [34, 35]) Rewards for power reduction (e.g. [36, 37]) Costs for power reduction (e.g. [38, 39, 29]) Delay in power provision (e.g. [30])
Time	Fairness at one time-point (e.g. [40, 41, 31, 42]) Fairness over previous time-points (e.g. [43, 44])
Control type	Feedforward (using forecast data) (e.g. [45, 16]) Feedback (using real-time data) (e.g. [27, 46, 47])

The search yielded 261 articles: 108 from Scopus and 153 from IEEE Xplore. After removing duplicates across the databases (resulting in 197 unique articles), we selected articles by scanning the abstracts based on two criteria. The first criterion was that the article discussed fairness principles or evaluation metrics in algorithmic control systems. The second criterion was that the article focused on congestion management in electrical distribution grids. After selecting eligible results based on scanning abstracts (82 articles), the complete articles were read and filtered for the same search criteria. This resulted in 54 articles for our literature review.

Three key aspects have been analyzed in the selected articles, as depicted in Figure 1. First, we analyzed how the problem of fairness was scoped within the context of congestion management. This involved aspects such as motivations for considering fairness, the types of congestion considered, and the types of burdens and benefits to be distributed. Secondly, the fairness principles considered in the selected papers have been analyzed, such as the uniform, proportional and social welfare fairness principles. Finally, the evaluation metrics used in the selected papers to assess these systems have been studied. These evaluation metrics are often used to determine whether the fairness principles are achieved, considering potential constraints such as physical limitations or competing objectives. The following sections provide our findings within these three categories.

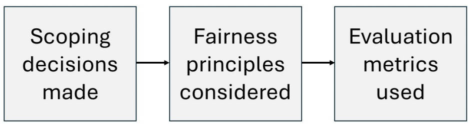

Fig. 1. Analyzed Aspects of Fairness Conceptualizations

III. FAIRNESS PROBLEM SCOPE

Table II outlines the scoping decisions identified from the selected articles. These include the motivation, type of congestion, application area, burdens or benefits to be distributed, time frame, and control type. Most studies concentrate on a specific combination of these scoping decisions, limiting the ability to compare the impact of different scoping decisions.

The scoping decision for a burden or benefit to be distributed *fairly* has a significant impact on the outcomes. For instance, aiming for equal provision of active power differs substantially from aiming for equal reduction of active power. However, many papers lack clear justification for their selection of burdens or benefits and do not consider how these choices impact the distribution of other burdens or benefits.

IV. FAIRNESS PRINCIPLES

Five main fairness principles emerged from the literature review. First, a *proportional* fairness principle aims to allocate resources based on certain properties of connected parties, such as their active power demand or installed generator capacity. Second, a *uniform* fairness principle strives for equal resource allocation among parties. Third, *fixed limits* set constraints on the distribution of resources, for example by ensuring that the resources of all parties remain below a specific threshold. Fourth, a *social welfare* fairness principle aims to achieve a global objective, such as minimizing curtailment. Finally, a *min-max* fairness principle aims to minimize the maximum burden or benefit among parties.

Many papers operationalize fairness principles in congestion management as optimization objectives and constraints. Table III presents mathematical formulations for each principle as examples. In these examples, consider a resource grid capacity U to be distributed among parties N, where u_n represents the allocated capacity for party n, $\bar{u}$ the average allocated capacity, V a resource for the proportional fairness principle (e.g., active power demand), and L_n a fixed capacity limit for each party.

TABLE III
EXAMPLE MATHEMATICAL FORMULATIONS OF FAIRNESS PRINCIPLES

Principles	Mathematical formulation
Proportional	$f = \min \sum_{n\in N} \left(u_n - \frac{v_n}{\sum_{m\in N} v_m} \sum_{m\in N} u_m\right)^2$
Uniform	$f = \min \sum_{n\in N} (u_n - \overline{u})^2$
Fixed limits	$u_n \leq L_n, \forall n \in N$
Social welfare	$f = \max \sum_{n\in N} u_n$
Min-max	$f = \min u_{\text{max}} \quad \text{s.t.} \quad u_{\text{max}} \geq u_n,\ \forall n \in N.$

Table IV provides an overview of how the identified fairness principles are conceptualized in the selected articles. Out of 54 reviewed articles, 50 articles applied a fairness principle in their congestion management algorithmic systems. It must be noted that some articles covered multiple fairness principles and may therefore appear in more than one category.

TABLE IV
FAIRNESS PRINCIPLES IN SELECTED ARTICLES

Principles	Options presented in selected articles
Proportional	Real-time active power production (e.g. [48, 49, 50]) Real-time active power demand (e.g. [40]) Forecasted active power production (e.g. [18]) Real-time reactive power production (e.g. [48]) Maximum generator capacity (e.g. [5, 33, 45, 4, 15]) Maximum flexible load (e.g. [1]) Net power export (e.g. [3, 5, 17, 36]) Real-time reactive power production (e.g. [45]) Congestion management rewards (e.g. [5, 33]) Revenue on electricity markets (e.g. [4]) Fees paid to distribution system operator (e.g. [51]) Contribution to overvoltage (e.g. [52, 3, 53]) Number of past requests (e.g. [54, 11]) Power reduction in past requests (e.g. [22]) Power provision in the past (e.g. [55]) Distance to transformer (e.g. [6]) Reliability in execution of requests (e.g. [29]) Time to deadline (for charging) (e.g. [19])
Uniform	Active power reduction (e.g. [56, 3, 13]) Active power provision (e.g. [35, 24]) Reactive power reduction (e.g. [57]) Reactive power provision (e.g. [47]) Among certain geographical areas (e.g. [14, 31]) Delay in obtaining requested active power (e.g. [30]) Within certain geographical areas (e.g. [12])
Fixed limits	Active power reduction below threshold (e.g. [41]) Eligible participants (e.g. [17]) Maximum number of requests (e.g. [32]) Maximum duration of a request (e.g. [32]) Minimum time interval between requests (e.g. [32])
Social welfare	Active power reduction (e.g. [7]) Financial compensation (e.g. [37])
Min-max	Minimize maximum active power reduction (e.g. [3]) Maximize minimum active power provision (e.g. [51])

It's important to recognize that while literature often uses the term *proportional fairness* as a single concept, many factors are used for determining this proportionality, as detailed in the second column of Table IV. Our analysis identified eighteen such factors from the selected articles. Authors however rarely justified why a certain factor was chosen for the proportional fairness principle in their algorithmic system.

V. FAIRNESS EVALUATION METRICS

Fairness principles serve as goals for algorithmic control systems in congestion management. However, the nature of the optimization problem can prevent these goals from being fully achieved in practice. For instance, certain objectives or constraints might be unachievable due to overlooked factors, ill-posed problems, or non-convergence of optimization algorithms. Therefore, fairness evaluation metrics are necessary to assess whether the objectives and constraints are met and whether these objectives and constraints are actually promoting a certain fairness principle. Additionally, fairness evaluation metrics can provide insights into the operational performance of the algorithmic control systems in practice.

Table V provides an overview of the fairness evaluation metrics considered in the selected articles. Four categories were identified: Jain's fairness index, averages, ratios, and the Gini coefficient. Jain's fairness index and the Gini coefficient were the most frequently used evaluation metrics, both promoting the uniform fairness principle, although Jain's fairness index has been adapted for the proportional fairness principle (e.g. [55, 31]). To clarify, Table VI presents mathematical formulations for Jain's fairness index [58] and the Gini coefficient [59] as examples, where u_n denotes the resource allocated to party n, and $|N|$ represents the total number of parties.

TABLE V
FAIRNESS EVALUATION METRICS IN SELECTED ARTICLES

Metrics	Options presented in selected articles
Jain's fairness index	Active power reduction (e.g. [5, 7]) Active power provision (e.g. [25]) Proportional active power reduction (e.g. [55, 31, 15]) Proportional active power provision (e.g. [19, 14, 16, 4]) Proportional financial benefit (e.g. [4]) Proportional net active power export (e.g. [4])
Average	Active power reduction time per participant (e.g. [32]) Relative distance to transformer for requests (e.g. [32]) Curtailment within a geographical area (e.g. [33, 12]) Percentage curtailment within an area (e.g. [33])
Ratio	Charging costs standard deviation over mean (e.g. [39]) Actual over estimated economic gain (e.g. [20]) Energy difference ratio (e.g. [51])
Gini coefficient	Charging time (e.g. [34]) Active power reduction (e.g. [13])

Most of the selected articles evaluate the same fairness principle applied in their algorithmic control system and do not evaluate the impact on other fairness principles, nor on the distribution of other burdens or benefits. Only Liu et al. [4] address this limitation. Three of the selected articles tested their algorithmic control systems against multiple fairness metrics (i.e. [32, 33, 4]). In contrast, many authors claim that their algorithmic control systems are *fair*, based on a single evaluation metric or without any evaluation metrics at all.

TABLE VI
EXAMPLE MATHEMATICAL FORMULATIONS OF EVALUATION METRICS

Evaluation metric	Mathematical formulation
Jain's fairness index [58]	$\frac{\left(\sum_{n\in N} u_n\right)^2}{\lvert N\rvert\cdot\sum_{n\in N} u_n^2}$
Gini coefficient [59]	$\frac{\sum_{i=1}^{\lvert N\rvert}\sum_{j=1}^{\lvert N\rvert}\lvert u_i-u_j\rvert}{2\cdot\lvert N\rvert\cdot\sum_{n\in N} u_n}$

VI. DISCUSSION

This study's analysis highlighted four main points for discussion. First, the motivations for incorporating fairness into algorithmic control systems were often not explicitly stated, yet they can significantly influence how fairness is conceptualized. Motivations ranged from aiming to minimize 'unfairness issues' to addressing specific instances of unfairness deemed unacceptable by actors. These motivations can also affect researchers' methodological approaches. For instance, public acceptance concerns might prioritize empirical validity, while normative concerns may emphasize philosophical interpretations or alignment with existing policy and regulation.

In addition to addressing motivations, the selected articles frequently lacked justification for design decisions regarding scope, fairness principles, and evaluation metrics. Future research should focus on developing standardized methods for these justifications to enhance transparency and rigor.

The selected articles primarily concentrated on applying fairness principles in their algorithmic control systems for congestion management, rather than on developing fairness evaluation metrics. Establishing common standards for evaluation metrics, alongside fairness principles, would unify the research community and enable more comprehensive empirical testing. More research is therefore needed to establish standardized metrics for assessing fairness in this context.

Moreover, the selected articles failed to address how different fairness conceptualizations were perceived by various actors in congestion management. Future research should therefore prioritize empirical studies to better understand the experiences of these actors, such as distribution system operators, regulators, and connected parties. This could involve field studies, surveys, and interviews. Such research would be instrumental in developing shared norms and standards for fairness in congestion management.

VII. Conclusion

This paper reviewed the literature on fairness in congestion management, exploring the different ways fairness is conceptualized. The analysis revealed considerable variation in fairness conceptualizations, highlighting a need for more explicit justification of design decisions. It also identified a need for more research on evaluation metrics to assess fairness and for empirical research on how different fairness conceptualizations are perceived by key actors. The presented categorization is not necessarily complete, but it may help others in conceptualizing and validating notions of fairness in the design of algorithmic systems for congestion management.

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